ID: 88081731
Box 13
Accordion 5
Item 13-67

United States Environmental Protection Agency | Policy, Planning, and Evaluation (2163) | EPA 230-R-95-012 April 1995

EPA

FRAMEWORK

Pressure
State
Response
Effect

A Conceptual Framework to Support the Development and Use of Environmental Information for Decision-Making

Environmental Statistics and Information Division
Office of Policy, Planning, and Evaluation

A CONCEPTUAL FRAMEWORK TO SUPPORT THE DEVELOPMENT AND USE OF ENVIRONMENTAL INFORMATION FOR DECISION-MAKING

Acknowledgements

This paper is a product of the Environmental Indicators Team of the EPA Environmental Statistics and Information Division (ESID), under the direction of N. Phillip Ross. The Team included Leader *Chris Solloway, Michael Colby, Margaret Conomos, Bill Garetz, Herbert (Pepi) Lacayo, Ingrid Schulze, Tim Stuart,* and *Pat Wilkinson.*

The paper is based on a previous draft monograph by I. Schulze, *Conceptual Approaches to the Development and Use of Environmental Indicators and Statistics for Decision Making* (12/93). Other ESID staff who made valuable contributions were: Judy Calem, Chap Gleason, Eleanor Leonard, James Morant, and Ron Shafer, and special thanks also go to Paul Cough of the Office of International Activities.

Valuable inspiration for this paper came, at various times, from the work of: EPA's Environmental Monitoring and Assessment Program (EMAP); Environment Canada and Statistics Canada; the Organization for Economic Cooperation and Development (OECD); the Netherlands' Ministry of Housing, Physical Planning and Environment; Bob Costanza (University of Maryland Center for Environmental and Estuarine Studies), Glenn Suter (Oak Ridge National Laboratories), John O'Connor and Robert Goodland (World Bank), and Bruce Bandurski (International Joint Commission/US & Canada).

Helpful comments and encouragement came from: Anne Kerr of Environment Canada; Albert Adriaanse from the Netherlands; Wayne Davis and Kim Devonald of the Strategic Planning and Management Division (ESID's sister division in OPPE/OSPED); Dan Tunstall, Allen Hammond, and Eric Rodenburg from the World Resources Institute; and members of the Inter-Agency Task Force on Sustainable Development Indicators, especially Ted Heintz and Don Rogich from the Dept. of Interior, and Rob Hendricks from the USDA Forest Service. Several reviewers also provided useful feedback on drafts.

A multitude of choices and decisions had to be made in the course of writing this paper, on issues that are highly debatable. Obviously, not all of the above experts will agree on every detail of the results, but their assistance is greatly appreciated. In the interest of brevity and readability, not every choice could be fully explained within the confines of the paper. We hope that readers will ask for clarification when they feel it is needed. All readers are cordially invited to make suggestions that they believe could improve the proposed framework.

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Acronyms Used

AQI	Air Quality Index
CFC	chlorofluorocarbon
EIA	Environmental Impact Assessment
EMAP	EPA's Environmental Monitoring and Assessment Program
EPA	United States Environmental Protection Agency
ERB	EPA/OPPE/OSPED/SPMD/ Environmental Results Branch
ESID	EPA/OPPE/OSPED/Environmental Statistics and Information Division
GIS	geographic information system
IBI	Index of Biotic Integrity
IJC	International Joint Commission, United States and Canada
ITFM	Intergovernmental Task Force on Monitoring Water Quality
NGO	non-governmental organization
NOAA	US Dept. of Commerce/ National Oceanic and Atmospheric Administration
OECD	Organization for Economic Cooperation and Development
OPPE	EPA Office of Policy, Planning, and Evaluation
OSPED	EPA/OPPE/Office of Strategic Planning and Environmental Data
PEP	"Population-Economy-Process" model (Statistics Canada)
PSI	Pollution Standards Index
PSR	Pressure-State-Response
PSR/E	Pressure-State-Response/Effects
SNA	United Nations System of National Accounts
SOE	State of the Environment
UK	United Kingdom
UN	United Nations
UNEP	United Nations Environment Programme
USFWS	United States Fish and Wildlife Service
VEA	valued environmental attribute

A CONCEPTUAL FRAMEWORK TO SUPPORT THE DEVELOPMENT AND USE OF ENVIRONMENTAL INFORMATION FOR DECISION-MAKING

Executive Summary

It has been said that the U.S. Environmental Protection Agency is "data-rich but information-poor." While millions of dollars are spent on environmental data collection in the United States annually, activities are often uncoordinated, so that much of the data may be incompatible, inaccessible to potential users, and/or of unknown quality. These factors exacerbate the difficulty of making valid secondary uses of the information, as is increasingly necessary, due to budgetary constraints and the urgency of decision-making needs. This suggests a need for an integrated system of compatible geospatial and other data, summary statistics, indices, etc., which can facilitate secondary uses of environmental information for decision-making.

An increasingly widely-used framework for organizing environmental information is the Organization for Economic Cooperation and Development's *"pressure-state- response" (PSR)* model, in which human activities are seen as producing *pressures* (e.g., pollutant releases) which may affect the *state* of the environment, to which societies then *respond* if the resultant changes are perceived to be undesirable. This paper proposes a framework which builds on the PSR model, in the following ways:

(1) A derivative category called *"Effects"* is added, for attributed relationships between two or more Pressure, State, and/or Response variables, resulting in a "PSR/E" framework.

(2) Human driving forces of environmental change, and pressures of non-human origin are also included in the framework. Distinctions are made in terms of specific sub-categories in which the State of the environment can be measured, and the types of entities making Responses.

(3) Each sub-category is elaborated with a generic menu designed to facilitate linking environmental information collection efforts to common sets of environmental values, goals, and priorities.

(4) The framework is consistent with a hierarchical view of ecosystems, allowing for the spatial nesting of environmental information, compatible with community- or ecosystem-(place-) based approaches to environmental management.

(5) It is compatible with assessment-driven approaches to indicator selection (e.g., EMAP).

In the proposed framework, "Pressures" have been defined more broadly than by the OECD. First, we include factors of human and *non*-human origin, because of the growing synergy between the impacts of natural processes and anthropogenic forces on the environment. Second, pressures have been divided into three sub-categories: underlying, indirect, and direct pressures. *Underlying* pressures include social and demographic forces, technological change, and policies that stimulate economic activities. *Indirect* pressures include human activities

(mostly but not exclusively economic activities) intended to benefit human welfare, as well as some "natural" processes and forces, such as nutrient cycles, volcanic eruptions, earthquakes, and meteorological events and cycles. *Direct* pressures include actual biophysical stressors on the environment, such as pollutant releases, resource extraction, and exotic species introductions.

The "State" [of the Environment] category is organized to reflect the "spatial nesting" of ecosystems at *global, regional,* and *local* scales, with an additional sub-category for environment-related *human health and welfare*. Societal Responses are sub-divided by type of entity making the response: *governments, the private sector, households and individuals,* and *cooperative efforts*. Figure 3 (page 15) provides a diagrammatic summary of how the PSR/E framework is organized, with alternative schematics provided in Table 2 (page 16) and Appendix A (page 33).

Each Pressure, State, and Response sub-category is further elaborated with an illustrative menu of elements, provided in Appendix B. Within the State category, these elements are society's "valued environmental attributes" (VEAs) – the attributes of ecosystems, human health, and welfare that are considered by society to be important and potentially at risk from human activities and natural hazards (e.g., biological integrity, landscape hydrologic functions, human respiratory or neurological functions, the recreational/spiritual benefits of wilderness, etc.). Reaching agreement on an essential core set of ecological VEAs is one of the most critical needs in the framework development process.

The approach proposed is consistent with emerging ecosystem or "community-based" approaches to environmental management, in which data are spatially-referenced, organized on the basis of ecologically-defined geographic units as well as administrative units. To make the framework operational, the generic menus of pressures, VEAs, and responses would need to be tailored to specific geographic units. Because an environmental information system cannot measure everything, priorities must be set – through a collaborative process with stakeholders – among the menu elements for different geographic areas and spatial scales. In addition, an ecosystem-based information system must take into account the multi-scaled nature of human-environment interactions, and permit local and regional environmental values, goals, and information needs to be *nested* and linked within national and international ones.

In the last section of the paper, indicator/data selection criteria and approaches for summarizing data for decision-makers (e.g., indices) are discussed. Indicators themselves should, however, be tailored to specific user needs, and are therefore not specified as part of this conceptual framework.

An environmental information framework is a tool, not a structure cast in stone. Its contents will evolve as our understanding of human-environment interactions improves and as society's environmental values evolve. Development of a framework would therefore need to be an iterative process, requiring collaboration among the numerous stakeholders in an information system, including EPA program and regional offices, states, the public, and other agencies that share environmental management responsibilities with EPA. Other programs and initiatives, including the Environmental Monitoring and Assessment Program (EMAP) and EPA's Environmental Goals Project, will also provide critical input to a framework for an environmental information system.

A CONCEPTUAL FRAMEWORK TO SUPPORT THE DEVELOPMENT AND USE OF ENVIRONMENTAL INFORMATION FOR DECISION-MAKING

I. Introduction

In the twentieth century, human societies have expanded over the face of the earth at an unprecedented rate. World population doubled between 1950 and 1986, while gross world product and levels of fossil fuel consumption each quadrupled (Daly, 1989a). Flows of matter and energy through the human economy are in many cases now similar in magnitude to the flows of natural cycles and processes (Vitousek et al, 1986). Society may be entering an era where natural capital (natural resources, biological species, and ecosystem services), as much as human and produced capital, is becoming a limiting factor in economic development (see Figure 1). These factors bring into question whether development as it has been practiced is sustainable.

As societies appropriate ever more of nature's resources and services, there is increasing recognition that greater care is needed in decision-making regarding their use. There is also agreement that decision-making must be based on sound information. This is evident from the increasing focus, both nationally and internationally, on "state of the environment" (SOE) monitoring and reporting, environmental performance reviews and sustainable development indicators. Moreover, as cumulative human impacts on the environment become increasingly apparent, there is a trend toward more holistic community- or ecosystem-based approaches to environmental decision-making (Slocombe, 1993; Grumbine, 1994; EPA, 1994c).

The purpose of this paper is to propose the development of a conceptual framework for a unified system of environmental information (geospatial and other data, summary statistics, indices, etc.). This framework would identify society's environmental values, goals and priorities on a geographic basis at various spatial scales. In doing so, it could help identify, link, and drive the collection of data to support ecosystem-based environmental assessment[1] and management, including assessment of the environmental sustainability of human activities.

1.1 What is a System of Environmental Information; What are its Uses?

The Environmental Protection Agency (EPA) relies on a vast patchwork of environmental, economic and social data from many different sources as a basis for its policy analyses and management decisions. The utility, accessibility, and cost-effectiveness of the data used by EPA could be significantly improved if the present patchwork of data sources were part of a larger, more coherent body of information.

EPA is already one of the largest federal users of spatially referenced (geographic) data, and as the Agency moves closer to a community- or ecosystem-based approach to environmental protection, its need for geographic data is likely to increase considerably. The usefulness of existing geographic data is seriously compromised by a lack of common standards and agreement on data uses, types and formats (NRC, 1993). The United States needs a coordinated national spatial data infrastructure, as recently endorsed in Executive Order 12906.

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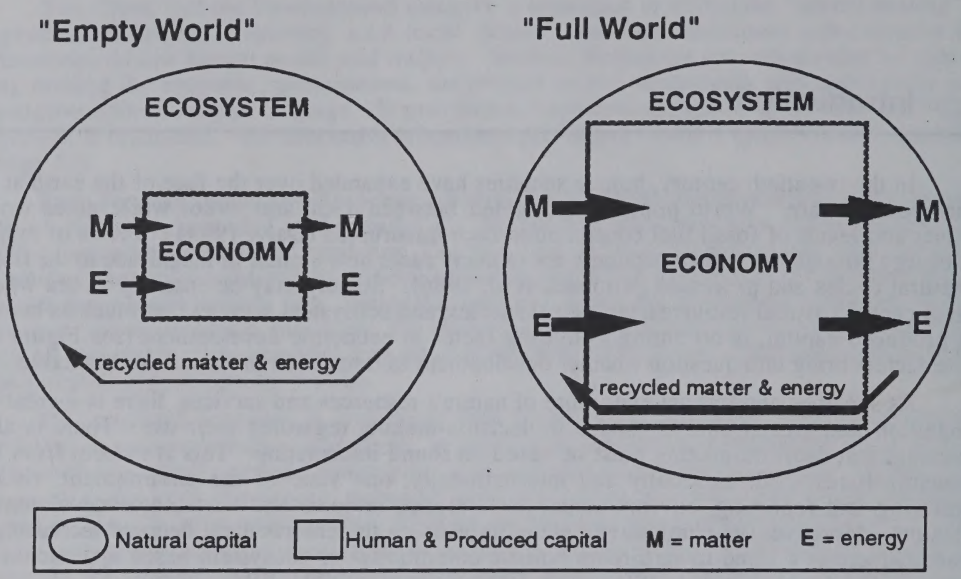
[1] Environmental assessment is defined here as analysis and interpretation of environment related data for use in decision-making.

Figure 1. A Growing Economy Embedded in a Finite Ecosystem



In the preindustrial, emptier world, the magnitude of the human economic subsystem was small relative to the large but finite global ecosystem. This has changed as the economy has grown, moving toward the "full world" scenario. The economy expropriates ever more material and energy from the ecosystem as resources, and subsequently releases more and more degraded matter/energy back into the ecosystem as pollutants or wastes. The scale of these "throughput" flows in many cases now compares to "natural" flows (e.g., carbon and water cycles, even primary [plant] production), so that the larger economy can be seen as interfering with some global ecosystem processes (e.g., ultraviolet filtration by stratospheric ozone, climate regulation, overall productivity). Thus, the extraction of resources and the discharge of wastes increasingly act as "pressures" on the environment's ability to maintain its "state of health," including basic life-support functions. These pressures in turn "feed back" on the economy, in that it must perform an increasing amount of the recycling function that nature did in the emptier world. (adapted from Goodland & Daly, 1993).

An environmental information system can be envisioned as a large array of environment related data series and other types of information, collected through networks of monitoring programs at multiple geographic scales which are integrated or coordinated at a number of levels. Ideally, such integration or coordination includes both data integration, and coordination at the level of the societal values, goals and priorities used to structure the system. Some important aspects of data integration include use of compatible definitions and classifications of variables; comparable field, remote sensing, and laboratory methods; compatible sampling design guidelines; and comparable database formats.

The contents of an environmental information system can include various kinds of quantitative and qualitative information, including both geographic and non-spatially referenced

data, summary statistics, indices, maps, projections of indicators in time, and various other kinds of model outputs useful for decision-making (e.g., risk estimates). An indicator is a parameter (i.e., a measured or observed property), or some value derived from parameters (e.g., via an index or model), which provides managerially useful information about patterns or trends (changes) in the state of the environment, in human activities that affect or are affected by the environment, or about relationships among such variables. Note that indicators, as defined here, can include information used in environmental management at any scale, not just by high-level policy-makers. Indices are aggregations of statistics and/or indicators, used to summarize often large quantities of related information. Maps, graphs, photographs, diagrams, etc., can be used to present both quantitative and qualitative information.

One existing example of an integrated information system is the United Nations' System of National Accounts (SNA), the widely used economic statistical system. The SNA is based on a theoretical model of the economic exchange/flow system, uses money as a common metric, and applies generally accepted concepts, definitions and classifications (UN, 1984). In contrast to the economy, however, there is no single macro-model of human-environment interactions which can be used to structure an environmental information system, and no common measuring unit. The dynamics of human-ecosystem interactions are at least as complex as economic dynamics, and they cannot readily be divorced from their spatial (geographic) context. Environmental interactions can be indirect, delayed, and highly nonlinear, and our understanding of these interactions is fraught with uncertainty. Thus, an environmental information system would have to be built on a variety of conceptual models, and include many different kinds of environmental and societal data and information.

The basic functions of an environmental information system are to support the assessment of environmental problems, and to facilitate reporting on these questions to policy-makers and the general public (usually under conditions of uncertainty). Environmental assessments typically seek to address one or more of three fundamental needs:

- Determine environmental and related societal conditions and changes (status and trends); i.e., is something happening that we should be concerned about?;
- Diagnose potential causes of detected problems or changes in condition;
- Predict or develop scenarios of future impacts of human activities, environmental change, and alternative responses to them.

Development of an operational information system also requires a detailed specification of user needs. For example, as a basis for developing its geographic information system (GIS), EPA's Region 2 has done an extensive analysis, on a program-by-program basis, of user needs for geographic data (EPA Region II, 1994b).

1.2 Why is a Framework Needed?

It has often been said that EPA is "data-rich but information-poor." Billions of dollars have been spent on environmental data collection in this country, yet many environmental management decisions must be made on the basis of insufficient or inadequate data. A conceptual framework for an environmental information system should help:

- link existing environment-related data to policy and management needs;
- integrate data sets on a geographic basis to support ecosystem-based decision-making;
- identify duplication and gaps in existing information collection efforts; and
- provide an impetus for the development of new data and indicators to fill gaps.

Several factors underlie this need for a unifying framework. The conceptual underpinnings of information collection, analysis, and interpretation are linked to environmental decision-making processes at several levels. At one level, information generation and use is driven by the statutory and regulatory framework (e.g., policy goals). At a deeper level, approaches to environmental assessment and management are also influenced by the philosophical paradigms that shape peoples' visions of human-nature relationships , and by the biophysical or scientific models used in environmental research and assessment (Colby, 1990). These paradigms and models shape the perception of problems and how people filter and evaluate evidence, at least in part because they predispose people to asking different sets of questions. Ideally, the legal/regulatory framework and the paradigms that influence decision-making should be compatible with the scientific ones used in environmental research and assessment. However, this has often not been the case. A conceptual framework for an environmental information system should strive to integrate the scientific, legal/regulatory, and philosophical paradigms that underlie information generation and use. Thus, a framework should do more than codify a collection of existing policy goals, and the resulting information system should be more than the agglomeration of databases from existing monitoring programs.

Emerging ecosystem approaches to decision-making can help form the basis for such a unifying framework. These approaches apply principles and methods of ecological science to the analysis and management of human-environment interactions. Some relevant characteristics of an ecosystem approach include the following:[2]

- inclusion of people and their activities in the ecosystem;
- viewing ecosystem structure and function at multiple scales;
- use of ecological boundaries to define environmental planning, assessment and management units;
- geographically comprehensive, systems-level analyses of interactions among physical, chemical, biological, and social components;
- adaptive management strategies, based on feedback from new information, to improve management and policy under conditions of uncertainty;
- participatory management involving all stakeholder groups;
- integration of science and human values in formulating goals for protecting ecosystem integrity; and
- recognition of ecosystem limits to action, i.e., defining and seeking sustainability.

Following this paradigm, a conceptual framework for an ecosystem-based information system should consist of hierarchical sets of environmental values, goals and priorities for ecosystems defined at various spatial scales, with sustainability of human activities as an explicit goal or constraint. Such a framework should seek to be anticipatory, by focusing on long-term and emerging environmental issues as well as more immediate regulatory concerns, in keeping with the intergenerational focus of the concept of sustainability.

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2 Ecosystem approaches reflect concerns about traditional reductionist approaches to environmental assessment and management, which tend, among other problems, to treat media (air, water, soil, and biota) independently, and inadequately address cumulative effects of multiple stressors. See, for example: Holling, 1978; Allen et al, 1993; Slocombe, 1993; Grumbine, 1994.

II. Existing Environmental Information Frameworks

At the simplest level, a conceptual framework is a mental model which provides a means of organizing thought processes or categorizing information about a subject. However, mental models are generally not a sufficient basis for integrating or organizing data, or for driving data collection. Most existing frameworks for environmental information collection, analysis, interpretation, and/or reporting have tended to be one of three general types:

(I) models of a decision-making process or strategy, that define, among other things, the relationship between indicators and societal values and/or policy goals, or

(II) models of environmental processes and human-environment interactions (i.e., simplified models of "the world"), which in turn tend to be of two types:

  (a) "causal" frameworks that classify environmental problems broadly in terms of the overall causal flow of human-environment interactions.

  (b) spatial frameworks that classify the land areas of interest where environmental problems are occurring.

In fact, these three types of frameworks are complementary, in the sense that they actually address different but equally important conceptual dimensions of the information generation process. The following sections will discuss each of these dimensions of a conceptual framework in turn.

2.1 Models of Decision-making Processes or Strategies

The term, "indicator framework" has been applied by the International Joint Commission/United States and Canada (IJC, 1991) to denote their conceptual strategy for developing ecosystem goals, objectives and indicators as a basis for ecosystem management of the Great Lakes. The term is used similarly by the Canadian Council of Ministers of the Environment (CCME, 1994). EPA's Environmental Monitoring and Assessment Program (EMAP) also describes their indicator development strategy as a framework, including linkage of indicators to ecological and human use values (EPA, 1994a). EMAP indicators are not necessarily linked to policy goals per se, since existing goals do not necessarily incorporate the entire range of ecosystem characteristics that society values.

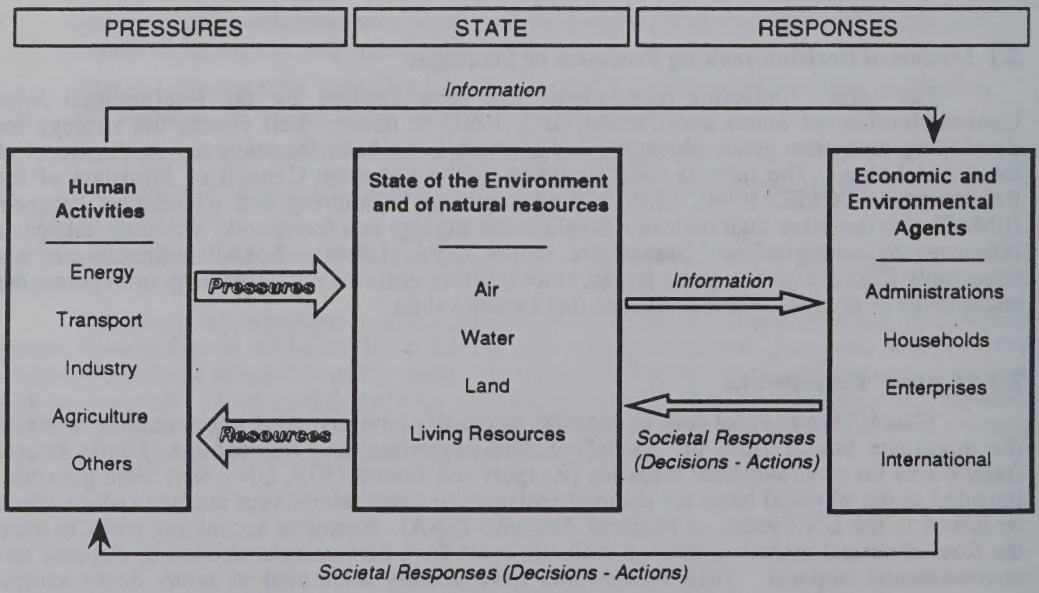
2.2 "Causal" Frameworks

"Causal" frameworks seek to organize or classify environmental information in terms of the aggregate causal flow or "cycle" of human-environment interactions. Early causal frameworks for environmental statistics (Rapport and Friend 1979, UN 1984) were generally intended as the physical basis for comprehensive environmental/resource accounts which could be linked to the UN System of National Accounts (SNA). Resource accounting seeks to trace the flow of natural resources through their life cycle from harvesting/extraction to disposal and environmental impacts. Such frameworks have usually attempted to break down natural resource stocks and human-environment interactions in a manner that maximizes the consistency with the SNA (UN 1984). A more recent environmental statistics framework with an explicit linkage to the SNA is Statistics Canada's PEP model (Hamilton, 1991; Statistics Canada, 1991).

Such environmental/resource accounting frameworks have striven for comprehensive coverage of natural resources and human-environment interactions. However, implementation typically has been restricted to a limited range of economically and politically important issues (e.g., oil and gas, timber, greenhouse gas emissions – Environment Canada, 1993), particularly ones that can be linked to macroeconomic models used in economic planning and environmental policy analysis (ERL Nederland BV, 1992). The Canadian PEP model has also been used to structure Statistics Canada's environmental statistics compendium.

A widely used simplification and adaptation of Rapport and Friend's (1979) early "stress-response" model is the Organization for Economic Cooperation and Development's "pressure-state-response" (PSR) framework (OECD, 1991, 1993). In contrast to the earlier "stress-response" model, which unrealistically tried to make one-to-one linkages among particular stresses, environmental changes and societal responses, the OECD PSR framework does not attempt to specify the nature or form of the interactions between human activities and the state of the environment. This simple PSR framework merely states that human activities exert pressures (such as pollution emissions or land use changes) on the environment, which can induce changes in the state of the environment (for example, changes in ambient pollutant levels, habitat diversity, water flows, etc.). Society then responds to changes in pressures or state with environmental and economic policies and programs intended to prevent, reduce or mitigate pressures and/or environmental damage. The OECD PSR framework does not specify the contents of the pressure, state or response categories, except in the broadest terms; see Figure 2.

Figure 2. OECD Pressure-State-Response Framework



The PSR framework is probably the most widely accepted causal framework at present, in part due to its simplicity and the fact that it can be applied at any scale. It has been used as a format for organizing state of the environment reports in OECD member countries such as the Netherlands,[3] for structuring the OECD's national environmental performance reviews (e.g., OECD, 1994), and for structuring possible sets of sustainable development indicators for the UN Commission on Sustainable Development and World Bank (SCOPE 1994; O'Connor 1994).

2.3 Spatial Frameworks

Historically, spatial frameworks for environmental assessment, planning, and management were organized by jurisdictional or administrative units (national, state, county, and municipality boundaries, census divisions). While readily understandable to the public and amenable to government action, these units rarely reflect patterns and processes of ecosystems. Alternatively, a number of land or ecosystem classification systems have been developed over the past twenty years to classify geographic areas for environmental management and planning purposes, based on common properties such as watersheds, climatic zones, vegetation, and soil types. Among the best known of these efforts are:

- US Geological Survey's land use/land cover classification system (Anderson, 1970/76)
- UNESCO's terrestrial vegetation-based classification system (Driscoll et al., 1983)
- US Fish & Wildlife Service's wetland/deepwater habitat classification system used for the National Wetlands Inventory (Cowardin et al, 1979)
- US Forest Service's *Ecoregions of the United States* (Bailey, 1976)
- Environment Canada's *Terrestrial Ecozones of Canada* (Wiken, 1986)
- Omernik's (1987) *Ecoregions of the Conterminous United States.*

For the most part, such land classification systems have been developed independently, to achieve different objectives, and lack compatibility with one another. Efforts have been made to hybridize some of the existing classification systems.[4] Some countries have developed national ecosystem classification systems which subdivide geographic areas into *regions* at various scales from ecozones down to ecoregions, ecodistricts, and sometimes still smaller spatial units.[5] Hierarchical ecosystem classification approaches based on the abiotic and biotic factors that govern the development/distribution of ecosystems (e.g., climate, geology, groundwater, surface water, soil, vegetation and fauna) have proven useful for environmental planning, management and reporting in various countries.

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3 The Netherlands' Environmental Policy Performance Indicators report (Adriaanse, 1993) uses the OECD's PSR model as a macro-framework, reporting on pressure, state, and response indicators for each of about ten major issues, and then looks at each economic sector to determine how much it contributes to each issue (problems or solutions).

4 One collaborative U.S. effort, led by the National Oceanic and Atmospheric Administration (NOAA), hybridized portions of the Cowardin and Anderson classifications (Klemas et al, 1993; Khorram et al., 1994). The U.S. Fish and Wildlife Service (USFWS) has hybridized the UNESCO, Cowardin, and Anderson systems for use in its Gap Analysis Program (Jennings, 1993).

5 E.g., Canada (Wiken, 1986), the Netherlands (Klijn and Udo de Haes, 1994), and Omernik's ecoregion approach used in the United States for surface water management (Hughes et al, 1986).

In general, ecosystem boundary definition is a thorny and somewhat arbitrary exercise, driven at least in part by the particular uses of classification (e.g., Gallant et al, 1989). In spite of the difficulties of defining ecosystem boundaries in a universally useful manner, however, government agencies such as EPA and the U.S. Department of Interior are increasingly focusing on ecosystem or community-based approaches to environmental management.

III. The Proposed Framework: Integrating PSR and Ecosystem-based Assessment

As noted earlier, the OECD's pressure-state-response framework is a simple macro-level model which has been used primarily as a format for organizing state-of-the-environment (SOE) reporting, national environmental performance reviews, and more recently, sustainable development indicators. It implies a general sense of causal progression: human actions serve as **pressures** on the environment, some of which may lead to measurable changes in its **state**, to which humans may then **respond** in an effort to reduce the pressures or prevent, repair or adapt to the impacts. The original OECD PSR framework was robust and useful, as is evident from its widespread application. However, it requires some clarification and refinement to be used as a basis for developing an ecosystem-based information system.

Section 3.1 proposes adding an "Effects" category to OECD's PSR, yielding "PSR/E," as the basis for developing an environmental information system. Section 3.2 discusses sub-categories of Pressures, State, Response, and Effects. Section 3.3 addresses the need to elaborate this PSR/E framework for specific geographic units at various scales. Section IV will then discuss some general approaches for setting priorities for information collection.

3.1 Extending the Pressure-State-Response Framework

In comparing the PSR framework to various other causal frameworks and environmental assessment programs, it was noticed that a variety of terms are used in different ways to cover similar categories. Some use the term "*response*" to refer to ecosystem responses to stresses, or *changes* in the state of the environment, while others use it to mean societal responses to *mitigate* such changes in state. Some use "*activities*" to refer to human pressures, while others use the same term to refer to societal responses. Some use "*effects*" or "*impacts*" simply to denote changes in the state, while others use it to indicate attributed relationships between pressures or societal responses and the state of the environment. Table 1 summarizes the terms used for analogous categories in a number of existing frameworks.

While cause-effect relationships are difficult to establish, environmental decision-making commonly relies on assumptions about (and plausible evidence for) such linkages in order to determine appropriate management responses. For example, the environment has the capacity to absorb (process) some stress, and data showing the presence of pressures alone is not an assurance that a significant change in the state of the environment has occurred as a result of that pressure. Furthermore, a change in state does not necessarily mean that there is a problem; even when there is, without knowing what caused the change, it is difficult to decide on a proper management response. Thus, models and analyses which show relationships among variables (e.g., environmental conditions and potential causes) generally have the most meaning for environmental decision makers.

Table 1. Typology of Causal Framework Categories (Nomenclature) [6]

Proposed Categories> / Organization:	PRESSURES	STATE	RESPONSES	EFFECTS
Statistics Canada/ *STRESS* (1979)	Activities, Stressors; Stresses, Natural Activity	Environmental Asset Stocks	*Collective & Individual* Responses	*Environmental* Responses
UN *FDES* (1984)	Socio-Economic Activities, Natural Events, some Inventories	Inventories, Stocks, & Background Conditions	*Human* Responses to Environmental Impacts	Environmental Impacts of activities/ events
Statistics Canada/ *PEP* (1991)	Flows: Wastes, Resources, & Services; Natural Processes	Natural Assets & Processes	Regulations & Perceptions	Envir. Benefits & Impacts on Individuals
Environment Canada (1991b)	Human Activity & Stresses	Conditions & Trends	*Management* Responses	
OECD *PSR* (1991) Netherlands (1993) World Bank (1994)	Pressures	State	*Societal* Responses	
ITFM (1992)	Stressors	Status & Trends	Management Actions	*Ecosystem* Responses/ Impacts
EPA/ ERB (1992)	Pollutant Releases (loadings)	Ambient Conditions	Activities [by Programs or by Sources]	Biological Effects (Human Health, Ecological Damage)
EPA/ EMAP (1993)	Stressors	Conditions		Associations

6 Note that the table shows broad similarities only. Definitions of the analogous categories used by different organizations are not identical, nor is (was) implementation of the frameworks necessarily equal to the conceptual models summarized here.

To address this need for information about relationships in decision-making, a fourth category, termed "Effects," has been added to the basic PSR-type framework, defined as indicators of *attributed relationships between two or more pressure, state and/or response variables*.[7] This category would contain whatever relationships are well-enough understood to make such attributions, derived from modeling and analyses of the connections between the primary variable categories. (Note that an Effect can be about a relationship between two different pressures – e.g., an underlying or an indirect and a direct pressure – as well as between a pressure or a response and a state variable, etc.) Effects information can be useful to help establish decision criteria for setting quantitative environmental policy goals.

3.2 Sub-Categories of PSR/E

Several of the frameworks compared in Table 1 have implicit or explicit sub-categories, within the Pressure, State, and Response categories. The following is an attempt to synthesize these existing frameworks into an elaborated PSR/E framework.

Pressures on the Environment

As alluded to in Figure 1, human-induced flows of many elements and compounds now occur at levels similar to the flows found in nature (e.g., nutrients, carbon dioxide, methane). Unfortunately, inventories of anthropogenic pollutant releases often neglect to compare them to natural flows, which may lead to inappropriate responses. Human-derived pressures now interact pervasively with natural processes. Simple, direct "environmental impacts" are being supplanted by more complicated webs of interacting, cumulative impacts. Phenomena that were once considered "acts of nature" are now better understood as often being caused or at least exacerbated by human activities (see Box 1). We propose assessing all direct pressures, then making an effort to distinguish between their sources (and relative scales), in a loose causal chain [web] from *underlying* pressures (of purely human origin) to *indirect* pressures (a mixture of human activities and natural processes), which in turn cause or contribute to the *direct* pressures:

- Underlying societal pressures are the social and technological forces that motivate or otherwise drive human activities, which in turn cause many of the direct biophysical pressures on the environment. E.g., human population growth, social structure, technology changes, cultural attitudes, and basic policies that drive economic activity.
- Indirect pressures are the *human activities* (mostly economic activities, e.g.: agriculture, mining, manufacturing, transportation, consumption by individuals and households) related to human sustenance or the improvement of human welfare, plus *natural processes and factors* (e.g., population and nutrient cycles, meteorological events, earthquakes, volcanic eruptions, etc.), many of which interact with human pressures and some of which act alone to create direct biophysical pressures on the environment.
- Direct pressures are the actual *biophysical inputs and outputs* that may exert immediate stress on ecosystems. These include anthropogenic pollutant releases, resource harvesting and extraction, land use changes, and species introductions. Also, the background *flows* (not the same as ambient levels or conditions) of those "natural"

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7 Diagnosis of causes of particular environmental or societal changes is usually difficult, and multiple causation is the norm rather than the exception. Determination of cause-effect linkages cannot rely on statistics alone, and a number of other criteria must be applied in order to conclude that cause-effect relationships exist (e.g., strength, specificity, consistency, biological or physical plausibility of an association).

stressors that are greater than or comparable to the anthropogenic pressures (perhaps within 1-2 orders of magnitude, if smaller).

Box 1. Escalating Interactions between Anthropogenic and "Natural" Pressures

Floods are often seen as an act of nature – the occurrence of high rainfall in a short period of time. However, human actions have grown to influence flooding in several ways. (1) When rain does fall, an area whose vegetative cover has been greatly altered (e.g., by paving surfaces or deforestation) will not be able to absorb as much of the rain, resulting in higher runoff and flash flooding. (2) Major river channels (e.g., the Mississippi) that have been straightened and cut off from natural floodplains (by dikes, etc.) will not be able to absorb and transmit the higher inflows from their tributaries, overtopping their banks. (3) Even in the absence of these aggravating factors, floods can be perceived to be worse than in the past, because more people live in or engage in economic activities (agriculture, resorts, other commerce) on the floodplains, so their effects in terms of higher human and economic damages are worse, even when the actual act of nature (the amount of water flowing) is no more severe. (4) Finally, humans may actually now be causing greater extremes in precipitation levels and storm events, by altering climate at a global scale (by changing the balance of the atmospheric gases that reflect or absorb heat). This is likely to result (if it has not already) in greater variability in precipitation patterns, which would indeed mean more severe floods and droughts...

Droughts and desertification have historically been considered to be a natural phenomenon that is the mirror image to floods: the lack of precipitation. However, long before the anticipated effects of global climate change are felt, micro-climate can be altered by humans at local levels. By denuding an area's vegetation (forests and other ground cover), local evapotranspiration cycles can be disrupted, resulting in less local rainfall, which further changes the vegetation cover, in a runaway feedback loop to more severe drought. When larger climate patterns (e.g., monsoons) do bring rain, the area is then more vulnerable to flash flooding because its capacity for absorbing the precipitation has been reduced, as described above. The flash floods in turn exacerbate soil erosion, which further decreases the ability to regenerate vegetative cover. As vegetation declines further, even less water is absorbed, and both the wet and the dry seasons become dryer...

Pest outbreaks tend to become more frequent, extensive, and severe where humans have disrupted population balances in ecological communities, usually by simplifying them (through monocultures) to concentrate productivity on one or a few particular species or strains. This creates a larger, denser, and less genetically variable host population for the pest, a phenomenon well-understood in the context of human disease epidemics as encouraging to the spread of a pathogen. Then, most widespread efforts to fight the pest outbreaks (or associated disease) involve the application of concentrated chemicals (drugs/biocides) which further simplify the ecological community if they kill not just the target (pest) organism, but also the organisms that would provide some natural controls on the pest species. And finally, the pest populations rapidly evolve resistance to the biocides, necessitating an ever-escalating battle, involving increasing the amount and/or the toxicity of the biocides, further simplifying the community, and so on...

At first, the inclusion of some natural processes and flows as pressures may seem confusing, or redundant with the idea of monitoring ambient conditions in the "State" category. This approach has been chosen as a compromise between two alternative paths. In the original,

basic PSR model, all "pressures" on the environment were human in origin. This approach is widely acknowledged as being too narrow – indeed too anthropocentric in an increasingly "full world" (see Figure 1, Box 1). At the other end of the spectrum, one could have separate subcategories for *indirect societal pressures* (human activities), which are in turn driven by the underlying pressures, and *natural pressures* (which are not). In practice, however, this would be difficult to implement. Again, as illustrated in Box 1, because multiple causality is the norm rather than the exception, it is all too often very difficult to distinguish precisely how much of a problem stems from each individual contributing factor. Therefore, we have "lumped" human and natural pressures together for now. Tables P.1 through P.3 in Appendix B provide detailed lists of the potential elements of each of the three pressure sub-categories.

State of the Environment

The State of the Environment category is concerned with ambient physical, chemical, biological, and ecological conditions; changes in ecosystem composition, structure and function at various spatial and temporal scales (including the "built" environment); human health; and environmentally-related welfare. There are a number of ways to sub-categorize State, e.g.,:

- by nested spatial scales (*Local*, *Regional*, and *Global* ecosystems), plus *Human Health* and *Environment-related Welfare*;
- by *Biological, Chemical, Physical,* and *Ecological* functions or variables.

Discussion in this paper will focus on the former approach, as shown in **Figure 3** and **Table 2**, (on pages 15-16) though a diagram for the latter is provided in Appendix A.

Ecosystems are characterized by complex interactions and feedback relationships among a multitude of potential stressors and receptors over a wide range of spatial and temporal scales. Ecosystems and their functions can be viewed in a hierarchical fashion, meaning that processes that operate at larger scales tend to control or constrain those at smaller scales (Urban et al 1987, O'Neill et al 1989). In addition, while some large scale properties of ecosystems can simply be treated as an aggregation of their component parts, others only emerge from the interactions of the component parts or processes. Thus, the usefulness of a nested spatial approach.

It is concerns about changes in or effects on "Valued Environmental Attributes" ("VEAs") that ultimately drive environmental decision-making. VEAs refer to those aspects of ecosystems (and human health and environmentally-related welfare, as discussed below) that are considered by society to be important and potentially at risk from human activities and/or natural hazards.[8] It is important to note that the societal value of ecosystems cannot be determined solely on the basis of public preference, since many people may be unaware of the value ultimately derived from ecosystem services. Over time, the number of ecological attributes found to be essential for maintaining the viability and stability of the biosphere (and therefore, economies and cultures) has continued to grow.

VEAs can range from individual valued species (e.g., trout species native to Yellowstone National Park), to landscape scale functions (e.g., hydrology of wetland systems), to global scale features (e.g., the stratospheric ozone layer's ability to filter ultraviolet radiation). Some VEAs are clearly already enshrined in existing legislation. For example, the Clean Water Act contains

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[8] One important theme in ecosystem management is the need to integrate scientific concepts with human values in developing policy goals. In ecological risk and impact assessment, various terms including "valued environmental components," "receptors," or "resources at risk" have been used to denote the valued attributes of concern in individual assessments. In the same way that valued attributes can provide a bridge between policy and science in individual assessments, they can provide a policy-relevant approach for helping to drive the development of an environmental information system.

an explicit goal of protecting biological integrity of surface waters, and this VEA has been operationally defined as "biotic integrity" for some fish and benthic communities. At present, no generally accepted, comprehensive classification of ecological attributes in policy-relevant terms exists.[9] Development of an information system should begin with a comprehensive effort to identify VEAs, followed by indicators for them.

The State Tables (S.1-S.3) in Appendix B include a provisional listing of VEAs at local, regional, and global ecosystem scales, as well as listings of pressures and other conditions whose ambient levels in the environment would need to be monitored. Much work remains to be done, however, if essential core sets of valued ecological attributes at different scales are to be defined in operational terms that can be measured.

Human Health and Welfare

Ecosystem approaches to environmental decision-making view humans as integral components of the ecosystem. Concerns about health and welfare impacts of exposure to pollutants are a central concern in environmental assessment. In human health risk assessment, the societal goal of protecting human health from environmental hazards can be defined in terms of lifespan and morbidity (diseases or disorders) of different functional systems of the body (e.g., circulatory, respiratory, immune systems) as well as psychological health (see Appendix B, Table S.4). Environment-related Welfare concerns include the economic value to humans of biophysical changes in ecosystems and human health, e.g.: value of marketed environmental goods, non-market use and non-use values, and the value to society of ecosystem functions/services. Non-economic measures can also be used, such as quality of life and equity. Sometimes environmental, economic, and social values may conflict with each other; different temporal scales may drive such conflicts.

Societal Responses to Environmental Change

Societal responses are defined as purposeful actions to address observed or predicted ecological, human health or welfare changes or impacts that are considered undesirable. The actions can be voluntary, legally mandated, or incentive-driven, and can be aimed at cleanup, mitigation, restoration, prevention, or adaptation. The societal response category can be subdivided by type of entity/actor making the response, e.g.:

- Government actions, including: environmental legislation, changes in fiscal/economic policies, regulations, monitoring, etc.
- Private sector activities, including: product and process redesign, waste treatment and disposal, cleanup efforts, changes in technologies used.
- Individual/household attitudes and actions, including: changes in consumption patterns, recycling, contributions to NGOs, etc.
- Cooperative efforts, including: research, education, land use planning commissions, public-private partnerships, international agreements, etc.

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9 Some potentially useful approaches have emerged. These tend to focus on terms such as ecological "integrity," "health," or "sustainability" (Woodley et al 1993, Angermeier & Karr 1994, Costanza et al 1992); ecosystem "functions" or "services" (Westman 1977, Preston & Bedford 1988, Ehrlich & Ehrlich 1992, Baskin 1994); or "biodiversity" (Fischman 1991; Ehrlich & Ehrlich 1992; Angermeier and Karr 1994).

Effects: Relationships among Pressures, States and/or Responses

Effects indicators concern attributed relationships between two or more variables within any of the P, S and R categories. They are based on models and analyses that provide plausible evidence of a linkage between a problem, potential causes, and/or solutions. In principle, indicators of this type should provide a relatively greater degree of certainty than just P, S or R indicators about what is happening, why, and/or what societal responses might be most appropriate. Sub-categories of Effects are not specified in Figure 3, but among the most important types of Effects are:

- Effects of Underlying Pressures on Human Activities (Indirect Pressures). E.g., effects of population growth on the energy sector.
- Effects of Human Activities (Indirect Pressures) on Levels of Biophysical Stressors (Direct Pressures). E.g.: CFC emissions associated with use and repair of automobile air conditioners.
- Ecological Effects (of Pressures or Responses on State). E.g., effects of: CFC releases on stratospheric ozone, exotic species introductions on native biodiversity, sewage treatment plants on water quality, regulation of lead in fuel on public exposure.
- Human Health Impacts. E.g.: lung cancer incidence associated with radon exposure; extent of mental retardation due to childhood lead exposure.
- Human Welfare Impacts. E.g.: economic and other costs of exotic species outbreaks such as Zebra mussels on aquaculture, shipping, recreation, and power generation; aesthetic and spiritual values associated with preservation of wilderness areas.

Figure 3 and **Table 2** summarize the subcategories proposed for the PSR/E framework. A series of tables in **Appendix B** offer a provisional listing of the contents of each of the P, S and R subcategories of the PSR/E framework, based on present scientific knowledge and policy concerns. Note that the Effects category of the PSR/E model does not require its own set of menus, as it represents a category of *functional relationships* between elements in the other (P,S,R) categories. The menus in the Appendix are as follows:

- Table P.1 Underlying Pressures (Sociotechnical Forces)
- Table P.2 Indirect Pressures (Economic Activities, Natural Processes & Factors)
- Table P.3 Direct Pressures (Biophysical Stressors)
- Table S.1 State of the Environment: Global Scale Ecosystems
- Table S.2 State of the Environment:Regional Scale Ecosystems
- Table S.3 State of the Environment: Local Scale Ecosystems
- Table S.4 State of the Environment: Human Health and Welfare
- Table R.1 Societal Responses: Government
- Table R.2 Societal Responses: Private Sector
- Table R.3 Societal Responses: Individuals/Households
- Table R.4 Societal Responses: Cooperative Efforts

Figure 3. Pressure-State-Response/Effects (PSR/E) Framework

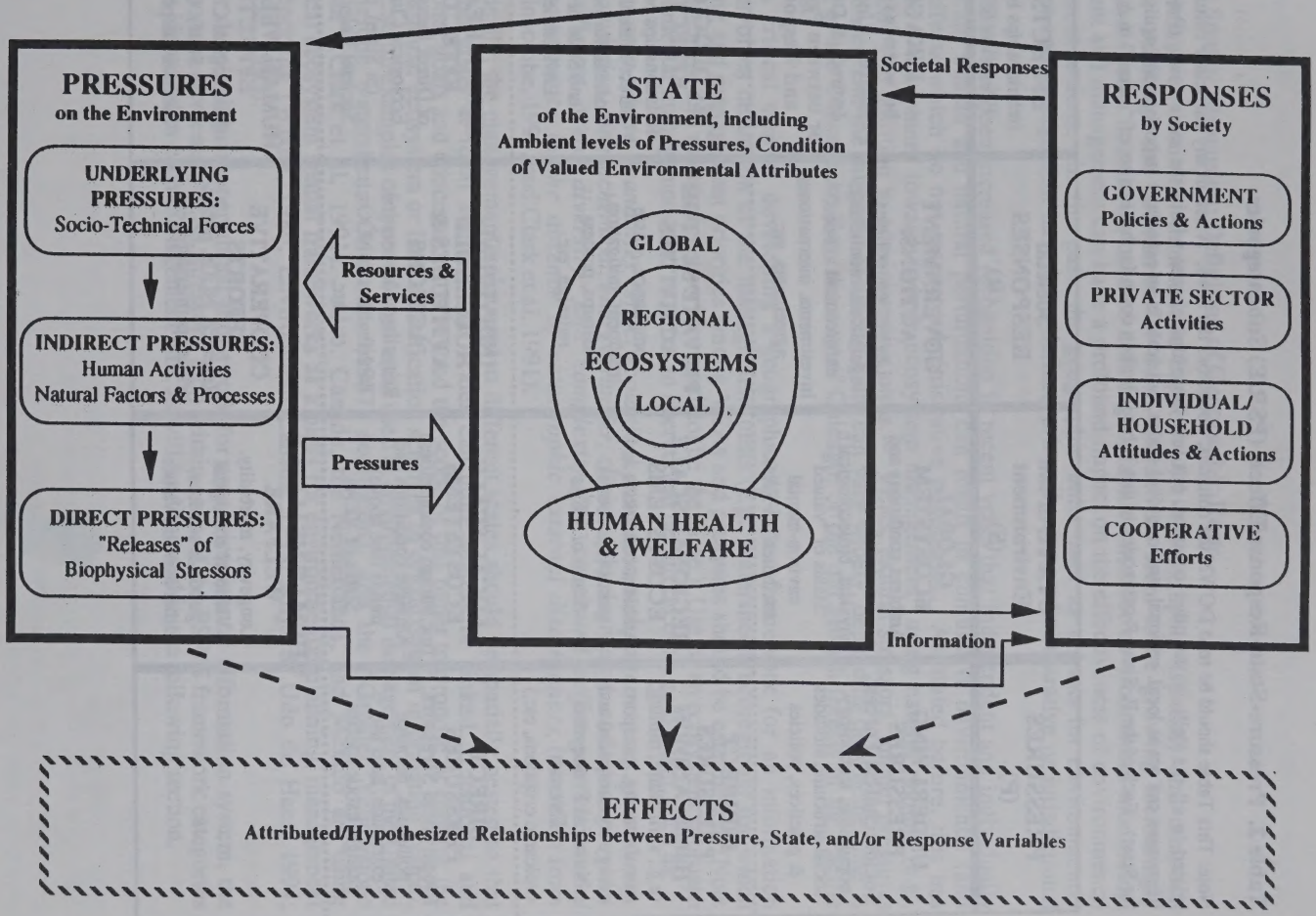

Table 2. Pressure-State-Response/Effects (PSR/E) Subcategories

Note: This Table should be read DOWN the columns, not across the rows. A cell in any particular column may be related to all the cells in the other columns, not just those that appear within the same row. (Pressures and Responses can act at local, regional, and/or global scales, but scale is an especially important distinguishing factor for State). Each of the P, S and R categories in this Table is broken down further in a set of "menus" in Appendix B.

PRESSURES (P)	STATE of the Environment (S)	Societal RESPONSES (R)	EFFECTS (E) (relationships between P,S and/or R) E.g.:
UNDERLYING PRESSURES **Sociotechnical Forces:** population, technology, social structure, attitudes & practices, policies	**GLOBAL ECOSYSTEM** Ambient conditions and trends (chemical, physical, bio/ecological); Status of "valued environ-mental attributes" (VEAs)	**GOVERNMENT ACTIONS:** Legislation, policies, regulations, monitoring, enforcement actions, investments, international agreements, etc.	**LINKAGES between levels of Pressures** (Underlying, Indirect, & Direct), **or between Pressures and Responses**
INDIRECT PRESSURES **Human Activities** (e.g., agriculture, mining, manufacturing, transport., energy consumption) and **Natural Processes/ Events** (volcanic eruptions, etc.)	**REGIONAL SCALE ECOSYSTEMS** Ambient conditions and trends (see above), Status of VEAs	**PRIVATE SECTOR ACTIVITIES** Compliance, waste treatment, mitigation, cleanups, process redesign, etc.	**ECOLOGICAL EFFECTS** Relationships between Direct Pressures or Societal Responses and State of the Environment
DIRECT PRESSURES **Biophysical Stressors:** pollutants, resource extraction, land use change, exotic species	**LOCAL SCALE ECOSYSTEMS** (inc.human communities) Ambient conditions and trends (see above), Status of VEAs	**INDIVIDUAL/ HOUSEHOLD ATTITUDES & ACTIONS** Recycling, conservation, contributions to NGOs, etc.	**HUMAN HEALTH EFFECTS** of Direct Pressures, Ecological Changes (in State), or Societal Responses
	HUMAN HEALTH & WELFARE Longevity, morbidity, Value of ecological goods & services, other non-use values	**COOPERATIVE EFFORTS** Research, NGOs, public-private partnerships, etc.	**HUMAN WELFARE EFFECTS** of Ecological Changes (in State), or Societal Responses

3.3 The Spatial Dimension: Definition of Geographic Units

Human-environment interactions happen within geographic (spatial) and temporal contexts. Although the boundaries for these interactions seem to be growing increasingly porous, the spatial boundaries used to define geographic units for environmental monitoring, assessment and management can have a profound impact on the effectiveness of environmental management actions. In the past, the geographic units used as a basis for environmental protection and management have been defined primarily along administrative or jurisdictional lines.

There has been increased recognition in recent years that independent and individually insignificant human and natural perturbations can result in cumulative environmental (and social) effects which do not respect administrative boundaries. As stated before, this has stimulated a movement toward "whole ecosystem management" using natural regions (e.g., "ecoregions") in addition to administrative units.[10] VEAs, natural stressors, human pressures and responses, and the interactions among them can vary widely, depending on whether one is speaking of the Chesapeake Bay, the city of Chicago, or the old growth forests of the Pacific Northwest.

A critical step in developing a geographically-based framework for an information system involves definition of the management units (e.g., watersheds, ecoregions) for which monitoring and management priorities among VEAs and pressures should be established. (Note that management and monitoring priorities need not be the same.) Use of an ecosystem approach to environmental management also requires an operational definition of an ecosystem, such as:

> *an area whose boundaries reflect ecological processes and patterns (e.g., community, population, biogeochemical, energy transfer, climate, physiography), and which provides sufficient area, diversity, and complexity for continued self-organization and maintenance in the absence of catastrophic external disturbances* (modified from Slocombe, 1993, and Clark et al, 1991).

Ideally, the management units used at different scales should be spatially nested so that values and goals at local and regional scales can more readily be linked to national and international goals and concerns. It is beyond the scope of this paper to propose or endorse the use of particular ecosystem or land classification schemes in organizing an information system. However, some examples of types of land units used in environmental management in the United States include watersheds, Omernik's (1987) ecoregions, and the "Greater Yellowstone Ecosystem" (Clark et al, 1991). Also, Canada, the Netherlands, and Mexico are using hierarchical ecosystem spatial frameworks as a basis for environmental planning, management and/or reporting (Wiken, 1986; Environment Canada, 1993; Klijn & Udo de Haes, 1994; (SEDESOL, 1993).

In developing an operational framework for an environmental information system, the most important elements (VEAs, stressors, etc.) within each of the PSR/E framework categories should be identified in each management unit, as will be discussed in the following section.

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10 E.g., efforts by EPA, NOAA, Dept. of Interior's Bureau of Land Management, and Dept. of Agriculture's Forest Service.

IV. Operationalizing the Framework: Setting Framework Priorities

4.1. Policy Goals and Monitoring Priorities

As discussed previously, existing environmental policy goals should be used to help set priorities for including data in an environmental information system. Existing goals alone, however, are an insufficient basis for determining framework priorities for an information system. Among other things, they address only those environmental values and problems that society has previously agreed to protect or manage. Generic policy statements entailing a discovery process, such as the National Environmental Policy Act's Title I, are an exception. In contrast, an environmental information system should address not only those issues about which a legislative or regulatory consensus for management already exists; rather, such a system should also focus on long-term and emerging environmental issues as well as more immediate regulatory concerns. Policy goals are also often vague about the specific environmental attributes requiring protection. Furthermore, environmental policy goals have primarily been established on a national basis, or in a fragmented and uncoordinated manner at subnational levels.

4.2. Refining the Framework: Setting Priorities on a Geographic Basis

Section III elaborated the contents of the PSR/E framework and discussed the fact that the framework can be applied in ecologically defined land areas at various scales. Review and discussion are necessary to decide whether the basic approach proposed in the previous sections is acceptable to stakeholders, and to revise it if necessary. Then, since everything in the menus cannot be monitored, a process could begin to set priorities among the elements of each menu provided in the Appendix. Such a priority setting process would be based on such factors as existing policy goals and program needs; assessments of the relative ecological, social and economic value of VEAs to society; and comparative analyses of risks to VEAs. Setting these priorities on a geographic basis at various (e.g., regional, global) scales, using ecologically defined land units, permits the entire array of pressures, VEAs, etc., that are important in a given area to be considered.

This priority setting process would allow the comprehensive menus in Appendix B to be reduced to essential core sets of framework elements for different geographic areas/scales. The priority setting process would be iterative, requiring collaboration among the many stakeholders in an information system, and must build on existing policy goals and monitoring priorities.

There are a number of possible approaches to setting framework priorities. Some general criteria for ranking the importance of VEAs for different areas/scales include: those which are essential "life support" functions for the biosphere (e.g., forests help regulate climate, prevent soil erosion, provide habitat for animals, etc.), and VEAs that are particularly unique, rare and/or valued, or are particularly vulnerable or threatened (e.g., due to cumulative stresses). Regional or resource-specific conceptual models can help in setting priorities. EMAP's Resource Groups are using a variety of conceptual models to identify the components of an ecological resource which contribute to system "values" (i.e., VEAs) such as biological integrity and ecological sustainability, to link indicators to societal values, and to identify expected relationships between stressors and indicators of ecological condition (EMAP, 1993).

Some criteria for prioritizing human health endpoints include severity and irreversibility of effects, high prevalence in the population, and/or strong evidence of environmental linkages. Note that, in general, people are more willing to accept some loss of components or functions of

ecosystems than impairment of their own health. Also, the parts of individual organisms, including people, are much more tightly coupled than the components of ecosystems. For example, people need both functioning circulatory and nervous systems to survive, but ecosystems are generally thought to have quite a bit of functional redundancy. Thus, human health-related priorities would be set on the basis of effects on body systems or functions (i.e., effects on VEAs) rather than first prioritizing VEAs themselves.

Some general approaches for prioritizing direct pressures on the environment include surveys to determine information needs of existing program activities (e.g., EPA Region 2, 1994), as well as use of methods such as comparative risk analysis and cumulative impact assessment. For example, the comparative risk approach taken by EPA's Region 6 (1990) in setting environmental management priorities could, in a modified form, also be used to help set framework priorities. The Region 6 analysis ranked risks of various stressor categories to a number of basic ecological functions (VEAs), using a geographic information system and Omernik's (1987) ecoregions as a spatial framework. Evaluation criteria included the severity, geographic scale and irreversibility of impacts. One limitation of comparative risk analysis is that it does not readily address cumulative effects of multiple stressors.

For human activities (indirect pressures), their "environmental efficiency" (environmental pressures produced per unit of value added to the economy or employment generated) is an important basis for including sectors in an environmental information framework. Thus, information about the energy, water and resource use and the pollution-intensity of different industries is important to consider. Note that due to economic and other large scale societal linkages, the environmental impacts of economic activities and policies (e.g., trade policies) and other underlying societal pressures (e.g., population growth) can cut across multiple ecological boundaries. Thus, priorities among economic sectors and other, underlying societal pressures must take into account administrative as well as ecological boundaries.

Important criteria for including societal responses in the framework for an information system are: responses which address the highest/largest scale environmental risks (e.g., global climate change), and those which are "upstream" in the causal chain (e.g., reductions in resource consumption and emissions, compared to cleaning up emissions after the fact), and are thereby potentially the most effective responses.

In sum, a variety of prioritization methods should be used iteratively to refine the framework menus. It is important to reiterate that an information system framework is a tool, not a structure cast in stone. It would not be immutable, but would evolve as our understanding of human-environment interactions improves and as society's environmental values evolve. In particular, it is critical to develop a core set of essential ecological attributes (components and functions) that need to be monitored at various geographic areas/scales over the long-term.

V. From Framework to Information System: Selecting Indicators and Summarizing Data for Decision-makers

The prioritization process discussed in the previous section would result in a framework calling for monitoring in different geographic areas at various scales. In order to use this as the basis for an operational information system, other steps are needed, including many levels of data coordination. A detailed discussion of the technical issues involved in establishing an information system is beyond the scope of this paper. However, two remaining topics will be discussed briefly in this section. The first is a general set of criteria for selecting the

indicators/data to be included in an information system. Second, since an information system should serve not just analysts and technical managers but also policy-makers and the public, some approaches for summarizing and/or visualizing data for decision-makers will be discussed.

5.1 Indicator/Data Selection Criteria

As described in previous sections, a framework for an environmental information system can guide variable or indicator selection and measurement by specifying the VEAs, goals and concerns that link data collection efforts to policy and management needs at various scales. Beyond that, the specific policy or management questions (e.g., about possible impacts of particular activities on wetlands), endpoints and hypotheses that a set of indicators should address must be tailored to meet the needs of individual organizations or programs. That is, they cannot be specified as part of a conceptual framework.

Environmental assessments can utilize either primary data collected specifically for the purpose for which they are used, or secondary data which were originally collected for other purposes. When basing assessments on existing data, analysts do not have the kind of control over factors such as data quality that they would if a new data collection effort were undertaken. In spite of these shortcomings, however, time and resource constraints frequently dictate the use of existing data. Various assumptions, models, and extrapolations are then applied in an effort to "adjust" the data so they can be used in a new assessment context (see, for example, Kineman 1993). Thus, the continuing need to use existing data as a basis for many environmental decisions is one of the most important arguments for the development of an integrated system of environmental information.

Indicator selection criteria (see **Table 4**) are a means of summarizing the most important characteristics that data collected in a monitoring program and/or used an assessment should fulfill. These characteristics help determine whether the indicators selected for a specific application can address the desired policy or management questions. The choice of criteria for a particular application depends in part on the intended use(s) of the indicator(s), and some selection criteria may be mutually exclusive. Indicator selection criteria are applicable to both primary data collection efforts and new uses of existing data.

Some of the most important indicator selection criteria relate to validity (including sensitivity), feasibility/ cost-effectiveness, and the existence of decision criteria that can help decision-makers determine when they should take action (e.g., environmental standards).[11] When existing data must be used to generate numeric values for an indicator, additional selection criteria become important, including data availability and the existence of adequate documentation (metadata) to allow potential users to determine whether a data set can be used for a specific application.

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11 Indicator interpretability (the existence of decision criteria that distinguish acceptable from unacceptable condition) is an often under-appreciated selection criterion that is critical if an indicator is to provide a defensible basis for decision-making. In statistical terms, such decision criteria or benchmarks are an essential part of the hypotheses that a data collection effort is designed to evaluate. From the policy standpoint, decision criteria are much more than part of a hypothesis, however, because they are the basis for often controversial decisions, in that they assume (for example) some level of acceptable environmental damage or human morbidity. Also, because biological thresholds are rarely known, such benchmarks or criteria are often based at least in part on other (social, economic or political) factors.

Table 3. Indicator/Data Selection Criteria [12]

Validity

Social and environmental relevance: Clear linkage to attributes, values or endpoints of concern (linkage can be direct or indirect, e.g., through a model).

Appropriateness of scale: Reflects conditions/changes at spatial and temporal scales appropriate to the environmental issue of concern.

Sensitivity: Has acceptable levels of uncertainty (i.e., signal sufficiently large compared to noise in data) to allow detection of meaningful differences.

Broad applicability to stressors: Responds to multiple stressor types (i.e., non-specific; important for screening level indicators).

Specificity: Responds specifically to particular stressors (opposite of broad applicability; important for diagnostic indicators for relating cause and effect).

Representativeness: Representative of behavior of system or other important parameters of interest.

Anticipatory: Provides early warning of undesired changes.

Historical record: Historical record available to define variability, trends and possibly acceptable and unacceptable conditions.

Feasibility/Cost-effectiveness

Measurability: Measurable by standard method with documented performance and low measurement error.

Timeliness: Data collection, analysis, and reporting feasible within decision-making timeframes.

Cost-effectiveness: Maximizes information per unit effort.

Non-redundance: Provides new information.

Data availability: Appropriate data exist and are accessible for secondary use.

Minimal environmental impact: of the sampling process itself.

Interpretability

Understandability: Is or can be transformed into form that is understandable by target audience.

Interpretability: Decision criteria can be agreed on which distinguish acceptable from unacceptable conditions.

Data comparability: Data collection methods (e.g., analytical methods, sampling design) comparable with other needed data sets.

Documentation/metadata: Adequate documentation to determine if data quality is adequate for intended secondary use.

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12 Adapted from: Kelly & Harwell, 1989; IJC, 1991; EPA, 1994a; ITFM, 1994.

Ultimately, the goal of the indicator selection process is to develop a suite of indicators for each element in the P, S and R framework categories, which address the major data needs/uses relating to that element (e.g., assessment of progress toward policy goals, risk assessment).[13] For reasons of economy, existing data would be used wherever possible. If existing data cannot be "redesigned" and its quality verified for secondary uses, this would suggest a need for new data collection.

5.2 Summarizing Information for Decision-Makers: Data Aggregation and Visualization

Technical specialists in organizations responsible for environmental protection and management require detailed information to provide a sufficient basis for quantifying environmental status and trends, determining whether conditions constitute problems, diagnosing potential causes of problems and their severity, and predicting possible future impacts of human activities and environmental change. Policy makers and the public, on the other hand, often have the time, interest, or ability to consider only a few pieces of information before they make decisions. Because an information system must serve the needs of a wide variety of users with varying degrees of technical expertise, methods and approaches are needed for summarizing and/or visualizing environmental information in user-friendly ways.

One commonly advocated approach for summarizing environmental information for decision-makers is through the use of indices, which use some systematic procedure to weight, scale and aggregate multiple variables into a single summary output. Indices can be constructed at various levels of detail and spatial scale, depending on the specific purpose of the index, and can be used to summarize data about individual VEAs such as "biological integrity." For example, Karr's Index of Biotic Integrity (IBI) and similar indices are being used increasingly in surface water management in the United States (Karr, 1991). The IBI is used to assess the condition of fish communities in midwestern streams. Similar indices have also been developed using other aquatic taxa and in other regions of the country. Another commonly used index is EPA's air quality index (also known as the Pollution Standards Index or PSI – Hunt et al. 1976), which is used to report local air quality to the public on a daily basis.

Indices can also be constructed for particular environmental issues or "themes," such as the environmental policy performance indices used by the Netherlands to assess progress toward national goals relating to global climate change, eutrophication, acidification, stratospheric ozone protection, etc. (Adriaanse, 1993). Each of the Dutch indices combines measures of the emissions of the most important pollutants (pressures) that contribute to a particular environmental problem, and weights these according to their relative contribution. For example, for global climate change, the index is expressed in terms of "CO_2 equivalents," and is a weighted summation of the Dutch contributions to emissions of greenhouse gases, weighted by the "global warming potential" (heat absorption capacity) of the individual gases. A line graph is used to depict progress of the index values toward future targets or goals.

A number of efforts have also been undertaken to develop highly aggregated indices for assessing the environmental, social and economic components of sustainable development at a national level).[14] Some of these approaches use dollars as a common measuring unit and seek to incorporate environmental pollution and/or natural resource depletion into national economic accounts or "satellite accounts;" other approaches use a combination of physical and economic aggregates. One example of a highly aggregated index that assesses non-sustainable resource

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13 One indicator can sometimes apply to multiple framework elements.

14 See for instance: Daly and Cobb, 1989, Goodland 1993, Pearce and Atkinson 1993, Hamilton and O'Connor 1994, BEA 1994, SCOPE 1994.

use in economic terms is an "index of net resource depletion" generated by the Scientific Committee on Problems of the Environment (SCOPE) in a draft report for the United Nations Commission on Sustainable Development. Quantifying long-term, irreversible losses of ecosystem components or functions in monetary terms and anticipating the values and preferences of future generations is difficult, if not impossible (EVF, 1992). Thus, assessment of ecological sustainability will continue to require biophysical as well as economic indicators.[15]

Some authors advocate multivariate statistical models as alternatives to weighted average indices for determining whether stressed biological communities fall outside normal ranges (e.g, Suter, 1993). Another alternative to data aggregation for making large amounts of data more accessible to managers and policy-makers is data visualization through graphical approaches, geographic information systems (GIS) and maps.[16] One simple graphical alternative for reporting ecosystem condition is Nip et al's (1990) "AMOEBA" approach. It permits visual integration of a number of indicators by presenting the indicator values as segments on a pie diagram, relative to a circle which represents the policy criteria or standards against which observed levels are to be compared. If all indicator values exactly meet the standards, then the diagram looks like a pie with equally shaped wedges. As more and more individual indicators fall short of or exceed the policy criteria (the circle), the diagram begins to look increasingly amorphous, like an amoeba. Multi-dimensional bar charts would be an alternative graphical presentation tool with a similar purpose.

In the future, spatial environmental process models (e.g., of atmospheric, hydrological or ecological processes) may provide policy analysts with more sophisticated decision-support tools that are easier to use than current models. Outputs from such models integrated with other spatial data using geographic information systems (GIS) are also potentially useful in helping decision-makers visualize complex, time-varying spatial interactions in the environment (see K. Fedra and others in Goodchild, Parks and Steyaert, 1993).

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15 "Early warning" indicators of ecological non-sustainability may actually be more readily recognized, for example, if some ecological thresholds have already been exceeded. Two potential candidates for such nonsustainability indicators include stratospheric ozone depletion, and the appropriation of net global primary production by humans (Vitousek 1986).

16 Indices can also be combined with these approaches.

VI. Conclusions

As EPA moves toward a community-based or ecosystem approach to environmental protection, the Agency will have an increasing need for geographically integrated data. This paper proposes a unifying framework for an environmental information system which is consistent with an ecosystem approach to environmental decision-making. Such a framework would be a useful tool to help integrate environment-related data on a geographic basis, identify duplication and gaps in existing data, and help drive new data collection. Some of the characteristics of the framework, building on the OECD's pressure-state-response model, include:

(1) A derivative category called "Effects" is added, for attributed relationships between two or more Pressure, State, and/or Response variables, resulting in a "PSR/E" framework.

(2) Human driving forces of environmental change, and pressures of non-human origin are included in the framework. Distinctions are also made in terms of specific sub-categories in which the State of the environment can be measured, and the types of entities making Responses.

(3) Each sub-category is elaborated with lists (generic menus) designed to permit environmental information collection efforts to be linked to a common set of environmental values, goals and priorities.

(4) The framework is consistent with a hierarchical view of ecosystems, allowing for the spatial nesting of environmental information compatible with community- or ecosystem-based approaches to environmental management.

(5) It is compatible with assessment-driven approaches to indicator selection (e.g., EMAP).

Implementation of an integrated ecosystem-based information system would require extensive collaboration among the stakeholders of the system. Some organizations or initiatives that could provide critical input to such a framework for an information system include: EPA program offices and Regions; the states; the Environmental Monitoring and Assessment Program, EPA's Environmental Goals Project, the Dept. of Interior's National Biological Service and US Geological Survey, NOAA, and other agencies with significant environmental monitoring programs; the Intergovernmental Task Force on Water Quality Monitoring (ITFM), the President's Council on Sustainable Development, and so on. Also, the U.S. is a party to numerous international environmental agreements that are relevant.

This process should probably begin with agreement on a basic macro-framework, either a PSR-type approach or some other model. Following that, a comprehensive effort should be made to identify priorities among potential framework elements in different geographic areas/scales. In particular, there is a need to agree on essential core sets of ecological attributes that warrant monitoring, in order to assess the environmental sustainability of human activities.

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Glossary

Assessment endpoint: expresses the specific policy question or hypothesis to be evaluated in an environmental assessment, and is the basis for indicator selection and measurement. A completely defined ecological assessment endpoint specifies the magnitude of the effect on a VEA that must be detected, the area that must be affected, the time allowed before effects are detected, and the acceptable level of uncertainty (adapted from Suter, 1993).

Biological integrity: the ability to support and maintain a balanced, integrated and adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region (from Karr, 1991). This concept has been applied primarily in surface water management. See also "ecological integrity."

Ecological functions: ecosystem properties that derive from the spatially structured interactions among many processes and the biological and physical/chemical components within a system (from Preston & Bedford, 1988). The term "ecosystem functions" may also be used interchangeably with "ecosystem services" (e.g., Westman 1977).

Ecological integrity: A living system exhibits integrity if, when subjected to disturbance, it sustains an organizing, self-correcting capability to recover toward an end-state that is normal and "good" for that system. End-states other than the pristine or naturally whole may be taken to be "normal and good" (H.A. Regier in Woodley et al., 1993). Another definition (from Karr & Angermeier 1994) is as follows: Biological integrity refers to a system's wholeness, including presence of all appropriate elements and occurrence of all processes at appropriate rates. Whereas diversity is a collective property of system elements, integrity is a synthetic property of the system. Unlike diversity, which can be expressed simply as the number of kinds of items, integrity refers to conditions under little or no influence from human actions; a biota with high integrity reflects natural evolutionary and biogeographic processes.

Ecological sustainability: maintenance of ecosystem components and functions for future generations.

Ecoregions: regions of relative homogeneity in ecological systems or in relationships between organisms and their environments (from Omernik, 1987).

Ecosystem: an area whose boundaries reflect ecological processes and patterns (e.g., community, population, biogeochemical, energy transfer, climate, physiography), and which provides sufficient area, diversity, and complexity for continued self-organization and maintenance in the absence of catastrophic external disturbances (modified from Slocombe, 1993, and Clark et al, 1991).

Effects: attributed relationships between two or more pressure, state, and/or societal response variables.

Environmental assessment: analysis and interpretation of environment-related data for use in decision-making.

Environmental indicator: a parameter (i.e., a measured or observed property), or some value derived from parameters (e.g., via an index or model), which provides managerially significant information about patterns or trends (changes) in the state of the environment, in human activities that affect or are affected by the environment, or about relationships among such variables. As defined here, indicators include geographic (spatially referenced) information, and information used in environmental management at any scale, i.e., not just for high-level policy-makers.

Environmental information system: a large array of environment-related data series and other types of information, collected through networks of monitoring programs at multiple geographic scales which are integrated or coordinated at a number of levels. Such integration or coordination can include data integration, and coordination at the level of the societal values, goals and priorities used to structure the system.

Environmental sustainability: long-term maintenance of ecosystem components and functions for future generations.

Framework: at the simplest level, a framework provides a means of categorizing information about a subject. Three important kinds of frameworks for environmental information collection, analysis and reporting are: models of a decision-making process or strategy, conceptual models of the "causal flow" of human-environment interactions, and spatial frameworks, i.e., ecosystem or land classification systems. These three types of frameworks are complementary and actually represent three dimensions of the information generation process.

Index: an aggregation of statistics and/or indicators, which summarizes often large quantities of related information by using some systematic procedure to weight, scale and aggregate multiple variables into a single summary output.

Pressures: human activities and natural processes, and the biophysical stressors derived from these activities and processes, which can contribute to stress on human health and welfare and on components and functions of ecosystems.

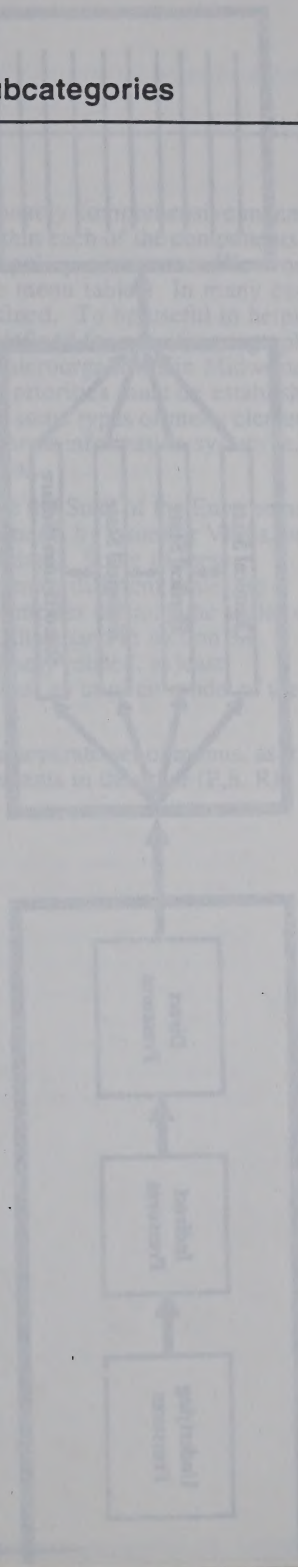
Responses: purposeful human actions to address observed or predicted ecological, human health or welfare changes or impacts that are considered undesirable; i.e., societal responses.

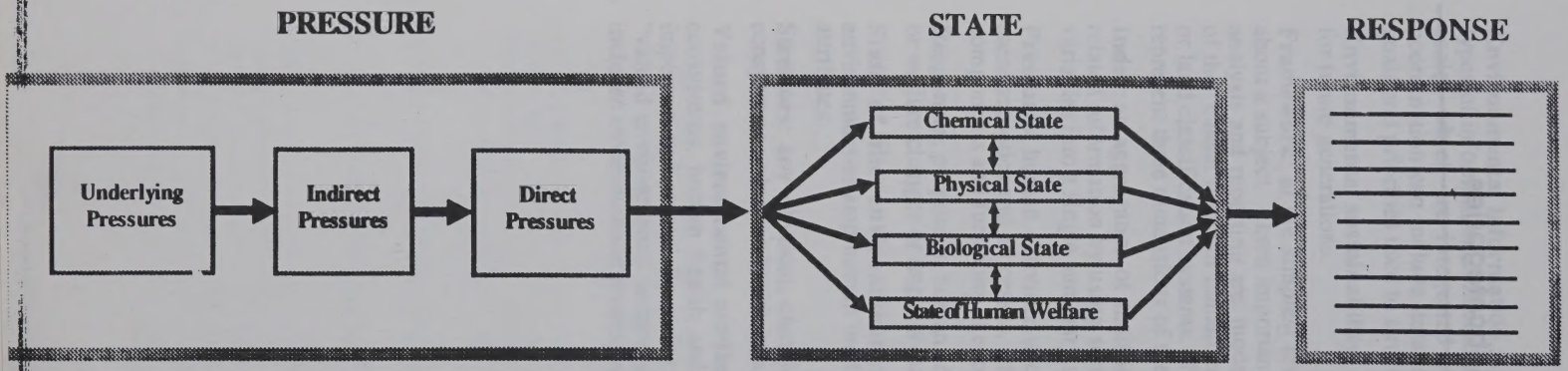
State of the environment: conditions and changes in ecosystems, human health and environment-related human welfare, including as a subset the condition of valued environmental attributes.

Stressors: any physical, chemical or biological entity that can induce an adverse effect on ecosystems or human health (adapted from RAF 1992).

Valued environmental attributes: those aspects (components or processes/functions) of ecosystems, human health and environmentally related welfare that are considered to be important and potentially at risk from human activities or natural hazards. Similar to the term, "valued environmental components," used in environmental impact assessment, but explicitly includes environmental processes as well as human health and welfare.

Appendix A: Other Schematic Views of PSR Subcategories





Basic Socio-Technological Factors:
- Population
- Technology
- Social factors
- Level of prosperity

Human Activities (by Economic Sector):
- Agriculture
- Forestry
- Mining and minerals
- Energy production
- Energy consumption
- Manufacturing
- Transportation
- Etc.

Natural Events and Forces:
- Meteorological events
- Volcanic and seismic events
- Etc.

Biophysical Stressors:
- Pollutant releases
- Land use
- Consumption of resources
- Diversion of resources
- Introduction of exotic species

Chemical State:
- Level of each chemical in air, water, or land

Physical State:
- Air temperature
- Water temperature
- Sea level
- Number and severity of storms
- Etc.

Biological State

Ecological State:
- Extent and condition of habitat
- Condition of particular species and groups of species

State of Human Health:
- Exposure to toxic substances
- Direct measures of health impact

The State Of Human Welfare

(For those aspects of welfare directly affected by the environment):
- Loss of recreation opportunities
- Damage to crops
- Etc.

Broad Measures:
- Expenditures on pollution abatement
- Expenditures on nvironmental services

Specific Measures

(Number of each specific kind of action taken for each):
- Pollutant of concern
- Type of source
- Environmental medium
- Exposure pathway
- Etc.

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Appendix B: PSR/E Sub-category Menu Tables

The following "menus" are an effort to present, in a reasonably comprehensive manner, the universe of elements (pressures, VEAs, societal responses) within each of the components of the PSR/E model, based on present scientific knowledge and policy concerns. We would appreciate hearing from readers about omissions or errors in the menu tables. In many cases only classes of elements (e.g., "biogeochemical cycling") are defined. To be useful in helping set monitoring priorities, ecological VEAs must be operationally defined for specific geographic areas (e.g., global carbon storage in forests, nitrogen fixation by microorganisms in Midwestern farmlands). To transform the menus into a working framework, priorities must be established among defined menu elements at various geographic scales. Also, some types of menu elements can potentially be seen as essential core elements of a framework for an information system (e.g., regional environmental diversity) and others would likely be optional.

In principle, there are a number of possible ways to organize the State of the Environment category: by scale, by ecosystem type or degree of alteration by humans, by issues or VEAs, or by data/indicator type (physical, chemical, biological or ecological data). Some of these categorizations are complementary. Ecosystems can be defined at many different scales, so categorizing the State of the Environment by ecosystem types also implies defining the scales of those ecosystems; this is really the purpose of a spatial framework, discussed in section 3.2. Categorization by environmental issues/problems and VEAs are closely related, at least implicitly, in that definition of an environmental issue requires at least an implicit model of the linkages between some pressures and one or more VEAs.

The Effects category of the PSR/E model does not require a separate set of menus, as it represents a category of indicators of relationships between the elements in the other (P,S, R) categories.

Table P.1 UNDERLYING PRESSURES (Sociotechnical Forces)

Population Structure and Processes
Birth & death rates
Population size; composition by age, gender, ethnic group
Migration rates; geographic distribution of population

Social/Cultural Attributes & Practices
Social/cultural attitudes, beliefs and values (e.g., toward recycling)
Individual & household behaviors, including voting, recreation, and product purchasing and use behavior
Other demographic variables:
- Distribution of income and wealth
- Household size and composition
- Labor force participation by gender
- Educational levels (especially scientific, environmental education)

Political Structures and Processes
Federal, state, local laws and regulations
Macroeconomic policies
Sectoral economic policies: e.g., agricultural, energy policies
Trade policies, e.g., North American Free Trade Agreement
Foreign aid policies, e.g., population-related policies
Organization of responsibilities, power relationships within/among federal, state, local governments (i.e., other than those captured above)
Organizational arrangements, power relationships within economic sectors, between business and government
Role of news media
Roles of voluntary associations
Land use/land development policies

Science and Technological Change
Basic and applied research, technology development with particular environmental applications or impacts, including scientific discoveries with potential environmental applications
Technology diffusion and displacement, by economic sector of application
Research and development expenditures by technical area
Science and engineering education and work force by technical area

Table P.2 INDIRECT PRESSURES (Human Activities, Natural Events/Forces)

Human Activities, generally by Economic sectors:

Production & consumption of commodities (goods & services) by industries in value terms (dollars)

Consumption of raw materials and intermediate inputs (including water) and production of goods and services and waste outputs, in physical terms, by industry on a geographic basis

Employment by industry, on a geographic basis

Commodity prices

Final consumption of commodities by households

International trade: imports & exports of processed goods & raw materials

"Natural" Processes & Factors:

Floods

Droughts

[Biological] Population fluctuations and migrations

"Biological" emissions (e.g., methane from termites, wetlands)

Fires

Hurricanes

Other climatic fluctuations (e.g., El Niño)

Earthquakes

Volcanoes

Table P.3 DIRECT PRESSURES (Biophysical Stressors) –of Human AND Natural Origin

Releases of Objects, Substances, Organisms, or Energy

Greenhouse gas emissions, emissions of ozone depleting substances
Other pollutant[17] emissions to ambient air and regional transport of pollutants
Applications of fertilizer, pesticides, salt; also releases from soil due to irrigation, etc.
Point source and non-point source discharges of toxic pollutants and nontoxic pollutants (e.g., nutrients, soil) to water
Pollutant emissions to indoor and workplace air
Contaminants in products, including food
Land disposal of nonhazardous, hazardous and radioactive waste
Chemical accidents, oil spills, leaking underground storage tanks
Translocation and proliferation of exotic [non-native] species or native "pest" species and disease vectors
Releases of genetically engineered organisms
Releases of radioactivity
Releases of heat
Noise, vibration

Harvesting and Extraction of Renewable and Nonrenewable Resources[18]

Commercial and sport fishing
Forestry
Agriculture (crops and livestock)
Aquaculture
Wildlife hunting and trapping, gathering of wild plants
Groundwater withdrawal/consumption
Mining/extraction/quarrying of metals, minerals, building materials
Extraction of petroleum, natural gas and coal
Ecological damage/ "natural harvest" by pests & predators, storms, fire, etc.

Land Use Changes

Construction of human settlements: urbanization, suburbanization (including development on beaches and barrier islands)
Conversion of natural ecosystems for agriculture, silviculture, aquaculture, mining, infrastructure (roads & highways, railroads, oil & gas pipelines, airports, power transmission lines, canals, dams, coastal waterways, piers, ports, seawalls, harbor dredging, etc.)
Diversion/channelization of river flows and construction of water resource projects
Various recreational land uses (other than hunting or fishing): camping, hiking, boating, swimming, use of off-road vehicles, etc.
Changes in land cover use due to fire, flooding, etc

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17 "Pollutant releases" here refers to releases of substances of human or natural (e.g., radon) origin that are considered undesirable by society.

18 Harvesting and extraction activities remove natural resources, rather than adding primary "stress agents" (e.g., pollutants, exotic species or highways) to the environment, though they also produce secondary stress agents, e.g., pollution due to mining activities.

Table S.1 STATE of the environment - the GLOBAL Ecosystem [19]

Valued Environmental Attributes (VEAs)

Stability of Global climate: atmospheric composition, temperature, precipitation patterns, storms, droughts, ocean currents

Integrity of the stratospheric ozone layer

Global scale genetic and species diversity

Global environmental diversity[20]

Biogeochemical cycling (and storage) of carbon, nitrogen, phosphorus and other elements

Energy fixation/primary productivity

Topsoil quantity and quality

Management of species migration

Environmental Conditions and Changes of Human and Natural Origin

Atmospheric levels of greenhouse gases; ozone depleting substances

Global temperature

Global habitat alteration and destruction, including deforestation

Global levels of soil erosion/degradation

Globally transported pollutants in air or water, e.g. to polar regions

Global changes in species occurrence and distribution

Proliferation of introduced (non-native) species

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19 Global scale VEAs can include systems or properties that operate/emerge at a global scale (such as the stratospheric ozone layer), as well as VEAs which function at smaller scales as well (e.g., species diversity) , but which have been sufficiently affected by cumulative human change that they must be monitored globally. Note that global and regional scale systems and changes tend to operate over longer time scales than local phenomena. Thus global and regional environmental change must be monitored and predicted over longer (intergenerational) time scales.

20 Environmental diversity encompasses ecosystem, habitat, community and landscape type diversity, including extent and spatial pattern.

Table S.2 STATE of the environment- REGIONAL Ecosystems

Valued Environmental Attributes (VEAs)

Regional genetic diversity, species diversity
Regional environmental diversity (i.e., types of habitat)
Biological integrity/health (e.g., Karr's Index of Biotic Integrity)
Primary productivity/energy fixation
Productive capacity of land for agriculture, forestry; soil quantity and "quality" (e.g., diversity of soil biota)
Air quality
Water quality
Productivity of valued plant or animal species
Stocks of nonrenewable resources: minerals, metals, fossil fuels, etc.
Hydrologic functions of landscapes: Flood regulation; Groundwater recharge; Water supply; Water filtration; River flows to support aquatic species, irrigation, recreation, transport, power
Geomorphological functions of landscapes:
Wind and wave buffering; Erosion control; Sediment retention
Stability of regional climate: precipitation, temperature, humidity, storms, etc.
Contaminant/pollutant detoxification, dilution, storage by media (including air, water, soil and sediments) and biota
Biogeochemical cycling, including eutrophication
Discrete landscape features valued for aesthetic, cultural, spiritual reasons: particular mountains, waterfalls, etc.
Habitat for wildlife, including migratory corridors
Natural pest control
Wilderness, open space

Conditions and Changes of Human and Natural Origin

Winds, ocean currents
Precipitation, flooding, droughts
Regional temperatures, humidity
Hurricanes, tornadoes, dust storms, other extreme weather events
Solar radiation; cloud cover
Glaciation, sea ice
Sea level
Landform geology; erosion, sedimentation, land slides & land subsidence, earthquakes, volcanic eruptions, Soil types
Drainage basins; changes in river flows; groundwater depletion
Soil erosion, compaction, salinization, and other degradation
Import/export of soil, nutrients, etc. to/from ecosystems; various nonpoint source pollution
Regional ambient levels of pollutants in media; long range transport of pollutants in air, water
Forest & grass fires
Ecosystem types, land cover/land use types (extent and spatial pattern)
Distribution of native species and communities; species loss, changes in species range
Feeding areas, habitats, migration routes of wildlife
Regional habitat destruction, fragmentation; succession/retrogression
Distribution, proliferation of exotic species, less desired native species, pests, disease vectors

Table S.3 STATE of the environment - LOCAL Ecosystems [21]

Valued Environmental Attributes (VEAs)

Safe drinking water (quantity and quantity)
Maintenance of hydrological & geomorphological functions (see regional menu)
Food safety (freedom from contaminants, undesired organisms)
Air quality (visibility, outdoor, indoor, workplace)
Pleasant climate (e.g., temperature, precipitation)
Tree cover
Natural control of "pest" and exotic (non-native) species
Pollination
Nutrient flows/cycles
Productivity of commercially, recreationally valued species
Local biodiversity and "biotic integrity;" healthy populations of local "keystone" and other desired species
Local environmental diversity
Proximity of homes to jobs, shopping, schools, parks, civic facilities
Access to local and regional transport (roads, public transport); safe routes for non-motorized traffic (sidewalks, bike paths)
Land availability for various uses: residential & commercial construction, agriculture, transportation corridors, parks, etc.
Utilities (electricity, communications networks, etc)
Sanitation (disposal, treatment, recycling options)
Recreationally, aesthetically valued locations/sites/vista
Other aesthetically and culturally valued attributes:
- Quiet
- Absence of noxious odors
- Cultural and historical sites and districts

Conditions and Changes of Human and Natural Origin

Quantity & distribution of land & water suitable for various human uses
Local climate
Pollutant levels, proliferation of disease vectors in air, water, soil, food
Proliferation of unwanted exotic species, less desired native species
Local habitat alteration/fragmentation, destruction
Trophic structure and functioning of ecosystems, including energy transfer, nutrient flows, etc.
Biological community structure: species diversity, niche structure, etc.
Condition of key species (individuals & populations), body burdens of chemicals; population size & dynamics
Extent and distribution of paved surfaces, etc.

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21 The local scale includes valued environmental attributes of human communities. Note that the state of VEAs of concern at the local level can also be monitored regionally or even globally.

Table S.4 STATE of HUMAN HEALTH AND WELFARE VEAs

Human Health and Health-related Economic Welfare:
Longevity (i.e., avoidance of premature death)
Appropriate physiological function of body systems (i.e., avoidance of morbidity for each of the following systems):
- circulatory
- respiratory
- nervous
- digestive
- musculoskeletal
- endocrine
- immune
- reproductive systems, etc.

Psychological health (i.e., avoidance of unnecessary environmental stress)

Health-related economic/welfare values:
- adequate income,
- time for family, work, & leisure

Value of Marketed Environmental Goods:[22]
Crops, livestock, timber, fish, shellfish, fur-bearing animals, other species valued for use as food, pets, etc.
Non-animal commercial inputs (chemicals, fertilizer, peat, metals, minerals)
Fossil fuels
Livestock forage
Water supply for: domestic consumption,, agriculture, energy production, industrial/commercial uses, waste disposal.
Land and water use for human settlements, transport (e.g.,navigation channels), etc.

Other Use Values:
Recreation and tourism: camping, hiking, boating, swimming,sightseeing, photography, fishing, hunting, meditation, etc.
Other aesthetic values (e.g., scenic views in residential areas)
Scientific and research value

Non-use Values:
Existence value
Historical, cultural, heritage & spiritual value
Bequest value
Intrinsic value
Scarcity/uniqueness value

Value of Ecosystem Services, marketed or not *(See S.1, S.2, S.3)*:

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22 In contrast to the VEAs in the other Tables, which address biophysical attributes of ecosystems and human health, welfare addresses the social and economic value to humans of biophysical changes in ecosystems and human health.

Table R.1 Societal RESPONSES - GOVERNMENT Actions & Policies

Federal, State and Local Government Responses:

Establishment of national, state and local environmental institutions, agencies and programs (e.g., creation of a Department of the Environment)

Integration of environmental policies into existing (e.g., sectoral) policies and institutional structures in all branches of government

Development of national environmental plans, strategies and goals

Information collection and analysis: e.g., government funded research and development, environmental monitoring and risk assessment, environmental accounting, environmental impact assessments, benefit/cost analysis

Information transfer and education: state of the environment reporting, environmental education, eco-labelling

Funding of public and private sector programs, projects and organizations (e.g., family planning programs, ecological research and conservation, R&D in cleaner technologies)

Implementation and enforcement of environmental regulations

Implementation of economic incentives (includes removing economic disincentives, e.g., subsidies for grazing, mining, logging on federal lands)

Pollution prevention, resource conservation by government facilities

Establishment of parks and protected areas

Land use planning by state and local governments

Environmental cleanup, ecological conservation and restoration on government land

Legislative actions not captured elsewhere

Table R.2 Societal RESPONSES - PRIVATE SECTOR Activities

Environmentally related research and development, e.g., development of CFC substitutes, drought-resistant crop varieties

Information collection and analysis, e.g., environmental auditing/life cycle analysis of products, environmental impact assessments

Information transfer and education: e.g., public disclosure of environmentally related data and information, environmentally responsible advertising

Voluntary, mandatory or incentive-based pollution prevention and resource conservation efforts (e.g., redesign of industrial processes to decrease resource inputs & waste outputs; designing more durable, energy efficient, less polluting products)

Internalization of environmental costs in product prices

Environmentally sensitive land use planning in development of new facilities

Waste treatment and disposal

Environmental cleanup and ecological restoration

Table R.3 Societal RESPONSES - INDIVIDUALS AND HOUSEHOLDS

Voluntary, mandatory and incentive-based pollution prevention and resource conservation by households (e.g., having smaller families, "green" product purchasing & product use behavior, reducing energy consumption)

Backyard, neighborhood ecological conservation and restoration efforts (e.g., landscaping with native plants)

Environmentally aware recreation behavior

Membership and participation in ad hoc environmental activities (e.g., voluntary beach cleanups) and NGOs (see below)

Voting, lobbying for "green" candidates and causes

Environmentally related philanthropy

Table R.4 Societal RESPONSES - COOPERATIVE EFFORTS

Environmentally related research and teaching in schools and universities

Partnerships between NGOs, businesses and/or government to reduce wastes, conserve/ restore resources, improve management practices (e.g., in wastewater treatment, energy conservation, forestry & fisheries)

Regional land use/ growth management/water resources planning commissions

Multilateral and bilateral international agreements: legally binding treaties, non-binding declarations and action plans

International organizations with environmental responsibilities (e.g., Organization for Economic Cooperation and Development)

Government advisory bodies, e.g., the President's Council on Sustainable Development, National Advisory Committee on Environmental Policy and Technology

Information collection and analysis (e.g., environmental monitoring and risk assessment)

Information transfer and education (e.g., environmental education, family planning education, state of the environment reporting)

Lobbying, litigation and less formal means of influencing government policy

Land acquisition/ecological conservation and other direct action